Power Converter Topologies for a High Performance Transformer Rectifier Unit in Aircraft Applications

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I. INTRODUCTION

Conventional aircraft usually employ a combination of hydraulic, electric, pneumatic and mechanical power transfer systems. Many companies are thus seeking to improve the efficiency of propulsive energy generation in order to decrease the weight of aircraft, therefore leading to a reduction in the cost of air travel through a better fuel economy.

New technologies can be applied with the aim of reducing life cycle costs through a reduction in periodical maintenance. However, all improvements must be made while taking into account that aerospace applications require high reliability [1-6]. In this way, electrical and electronic driven system technologies such as ice protection, environmental control systems, brakes, or the primary flight control actuator system have been used to replace the conventional ones [6, 7].

The recent developments achieved in power electronics as well as fault-tolerant distribution system technologies can be employed with the aim of attaining advanced aircraft power systems, which are able to substitute the heavy mechanical, pneumatic and hydraulic driven equipment. [1, 4].

The aircraft industry is moving towards the adoption of More Electric Aircraft (MEA) and All Electric Aircraft (AEA) technologies, which employ electrical power to drive airframe subsystems, flight control actuations, environmental control systems (ECS), ice protection systems (IPS), and other minor systems. These technologies would not only improve aircraft safety and reliability, but also could provide a reduction in the weight, fuel use, and emission of air pollutant gases associated with aircrafts. Besides this, energy savings can be increased along with a reduction in costs associated with maintenance, design, development and testing [3,10-12].

The present trend in the aircraft industry is to replace hydraulic and pneumatic systems by electrical systems achieving more comfort and monitoring features. In addition, this new distribution system can be used in generation, storage and conversion systems, thus improving aircraft reliability and performance [3, 7, 12, 13].

However, in order to obtain the significant characteristics offered by the MEA and AEA technologies described herein, it is important to adequately select the power electronic converter topology to be employed in all aircraft systems [14-15, 19-20, 24-26]. This fact should be taken into account when considering the Transformer Rectifier Unit (TRU), which combines the functions of a transformer and a rectifier into one unit. In aircraft applications, the TRU converts the AC voltage generated by the engine or generators to a DC voltage, which can then be used by various electrical components incorporated into the system [1-3].

The present challenges for Active and Isolated Rectifier Units (High Performance TRU) are to support the MEA and AEA in the demand for profound changes compared to the conventional TRU. The High Performance TRU demand new requirements as follows [1-3]:

- Low weight;
- Low Total Harmonic Distortion (THD);
- High Power Factor (PF);
- High temperature;
- Battery charger capability;
- Over-voltage and over-current protections;
- Degraded operation under 1-phase failure (in some applications);
- High efficiency and High reliability.

This paper presents some architecture and power converter topologies that can meet the requirements demanded by High Performance TRU, some of which were developed by the Centro de Electrónica Industrial (CEI) from the Universidad Politécnica de Madrid (UPM).

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Figure 1. Electrical architecture for High Performance TRU.

II. BASIC ARCHITECTURE OF HIGH PERFORMANCE TRU

A basic architecture that allows a High Performance TRU is shown in Fig. 1, where:

A. EMI filter which meets the EMI standards [16-22];
B. Active Three-Phase Rectifier (ATPR) to control the sinusoidal current demanded (THD - Total Harmonic Distortion and PFC – Power Factor Correction) as well as control the output DC link voltage ($V_{BUS\ DC}$) [2, 14-33, 40-45];
C. Isolated DC/DC converter that provides galvanic isolation, adapts the voltage and power to the specifications ($28V_{DC}$ or to a new grid value of $270V_{DC}$) and which can be put in charge of some control capabilities (battery charge mode, voltage source mode, current source mode, along with some forms of protection) [34-39, 46-56].

The specifications demanded for these new applications make the selection of the whole architecture critical along with the topology for each TRU block.

A. EMI Filter

The EMI standards applied need to be considered in the design of the ATPR EMI input filter, mainly [16, 17, 21]:

- to ensure sinusoidal shape of the input current by filtering the switching-frequency harmonics;
- to attenuate the electromagnetic interference with other electronic systems;
- to avoid susceptibility of electromagnetic emissions from surrounding systems and itself.

The 10kW EMI filter, developed by CEI-UPM, for a High Performance TRU with interleaving of three interleaved rectifiers is shown in Fig. 2.

B. Active Three-Phase Rectifier - ATPR

The use of ATPR makes it possible to meet the demands made by the THD and PF requirements as well as provide full control capability: battery charge operating mode, voltage source mode, overvoltage protection, under voltage protection, etc.

Figure 2. The 10kW EMI filter of a CEI-UPM High Performance TRU.

Besides this, the ATPR can operate at high switching frequencies (tens or even hundreds of kHz, depending on the application), allowing for a greater reduction in the size and weight of the capacitors and inductors, since the active three-phase rectifier is non-isolated.

The ATPR can function keeping its output voltage to a constant value, independent of the actual mains voltage. Consequently, the DC-DC converter stage could be dimensioned to a narrow voltage range. In addition, the ATPR can provide the following requirements [19]:

- high PF with sinusoidal input current;
- regulated output voltage;
- continued operation in case of mains failure (interruption of one mains phase);
- unidirectional power flow;
- compliance with EMI specifications

There is a wide variety of circuit topologies, which are able to reach Active Three-Phase Rectifiers [2, 14-33, 40-45]. However, the four topologies [20], shown in Figures 3 to 6, are quite promising for performing a High Performance TRU with high power density. These topologies are compared in [20] by using the Pareto Front Performance Space with the same specifications: output power of 10kW, line-to-line mains voltage of 400V, mains frequency of 50 Hz, and two different switching frequency 48kHz and 24kHz. For the boost-type systems the output voltage of 700V and for the buck-type systems 400V were used.

The topology shown in Fig. 3 is the simple, robust and well-known six-switch boost-type ATPR with bidirectional power flow [20]. However, the converter can operate in the unidirectional mode by employing an adequate control strategy, such as space vector control [40-44]. In addition, the phase-oriented PWM-based control, to be less complex, can be considered mainly when the converter operates at phase loss [45]. This two-level output voltage topology can provide high efficiency but presents some drawbacks, such as: higher semiconductor voltage stress due to the boost-type characteristic, limited switching frequency, large volume of input inductors, and the reduced reliability due to the possible shoot-through of a bridge leg, which results in a short circuit of the DC link voltage [27].

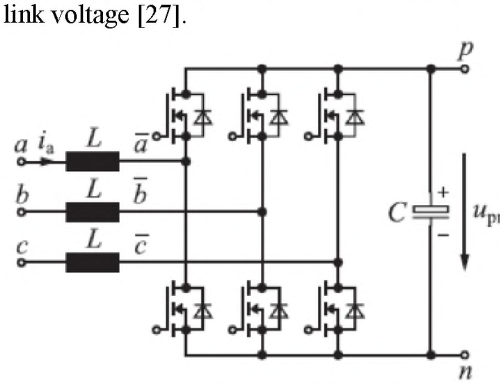

Figure 3. Six-switch boost-type ATPR (bidirectional) [20].

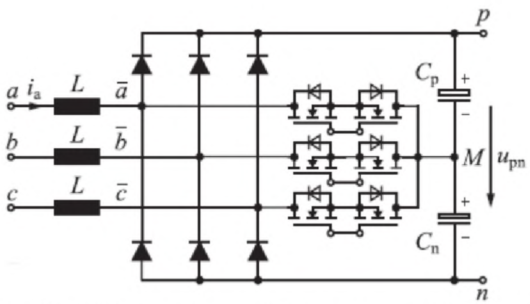

Figure 4. VIENNA three-phase rectifier (boost-type unidirectional) [20].

Fig. 4 shows the VIENNA Three-Phase Rectifier, which is a boost type unidirectional power flow [19-20]. This topology presents a reduced semiconductor voltage stress due to the three-level characteristic, low switching losses, low EMI and requires low input inductance. In addition, in the case of a phase loss, this converter can still be operated at a reduced output power and at the same output voltage with sinusoidal input currents in the remaining phases. However, it presents higher circuit complexity and requires the control of the output voltage center point [19].

The six-switch buck-type ATPR with unidirectional power flow is shown in Fig. 5 [19, 20]. This converter, due to the buck-type characteristic, can present low semiconductor voltage stress and there is no middle-point that has to be stabilized as in the VIENNA converter. Further, the DC current distribution to all phases can be controlled and this converter presents the potential of a direct start-up and the overcurrent protection in event of an output short circuit. However, it presents a reduced output voltage control range with low THD in the input current to wide load variation, due to the capacitive input filter. For this reason, this topology is more frequently indicated to fixed mains frequency. Also, the total semiconductor losses are dominated by the conduction losses due to the impressed DC current, and it presents pulsating input currents and requires EMI filtering [18, 25,33].

The SWISS rectifier, shown in Fig. 6, uses the third harmonic current injection concept. In this converter, the

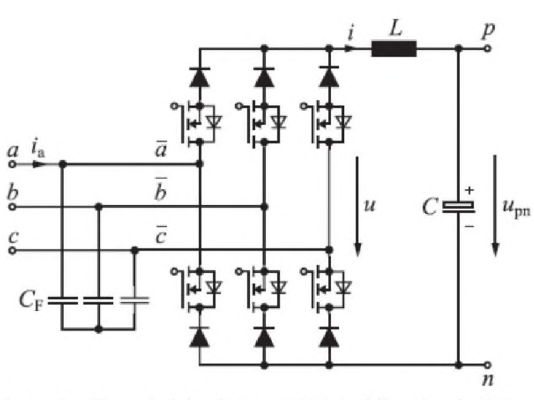

Figure 5. Six-switch buck-type ATPR (unidirectional) [20].

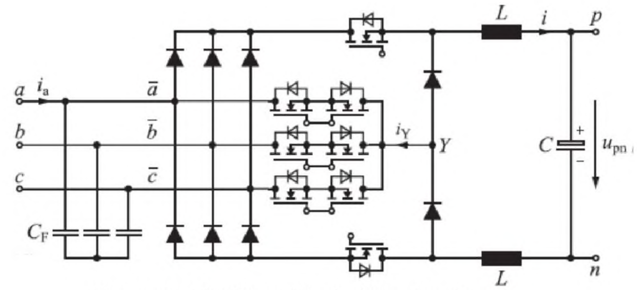

Figure 6. SWISS rectifier (unidirectional) [20].

rectifier diodes are not commutated with switching frequency. Correspondingly, the conduction losses can be reduced by employing devices with a low forward voltage drop (and a higher reverse recovery time). It can operate in an open loop control mode with a constant reference voltage value. In addition, it presents a purely sinusoidal mains current, low current stress on the injection current distribution power transistors, short circuit current limiting capability, also, it allows to generate low output voltages and presents low control complexity. On the other hand, compared to the Six-Switch Buck-Type ATPR it presents a higher number of active power semiconductors and the switching losses are concentrated on the two transistors in the positive and negative bus with a higher commutation voltage. Besides, it employs an AC-side capacitive filter, which results in a fundamental reactive power consumption [20, 25, 57].

C. Isolated DC-DC Converter

There are many high efficiency topologies of the DC-DC converters some of which are presented in [34-39, 46-56]. However, four different concepts, which employ the full-bridge DC-DC converter, seem very promising for performing a High Performance TRU with high power density.

In 1991, De Donker presented the first bidirectional three-phase DC-DC converter, known as Dual Active Bridge, which uses the leakage inductance and phase-shift (PS) concept to control the power delivery [48, 51]. A zero-voltage and zero-current-switching (ZVZCS) full-bridge PWM converter, which employs a simple auxiliary circuit, was introduced in 1999 by the authors of [52]. This circuit consists of one small capacitor and two small diodes, which is added in the secondary to provide ZVZCS conditions to primary switches, as well as to clamp secondary rectifier voltage. In 2000, Ionel Dan Jitaru proposed the operation of the full-bridge DC-DC converter with a bridge rectifier circuit in the secondary by using a triangular discontinuous current waveform [53]. Vinciarelli introduced the Sine Amplitude Converter concept in 2006 [54].

Currently, CEI-UPM is applying these concepts to the full-bridge DC-DC converter. The first topology, shown in Fig. 7, is a full-bridge DC-DC converter with one magnetic component. This topology employs the transformer leakage inductance to obtain a triangular discontinuous current that

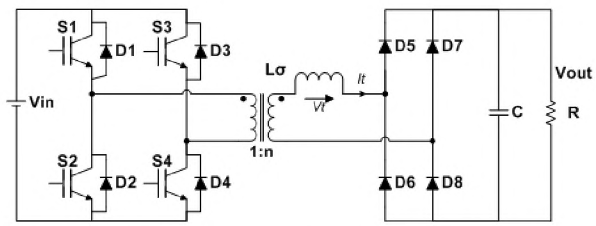

Figure 7. Full-bridge converter with triangular discontinuous current [46].

provides soft switching in almost all transitions and increases power density and efficiency [46, 53]. The converter switches perform Zero Current Switching (ZCS) and the diode bridge achieves soft transitions, which reduces the reverse recovery effect. The peak current control allows the parallel operation, short circuit and overcurrent protections to be easily implemented [46]. A 3kW/250kHz converter was built with three 1kW modules connected in parallel and achieved efficiency at full load of 96% with a power density of 110W/inc^3, as reported in [53].

The second topology, which employs the Dual Active Bridge (DAB) concept, is shown in Fig. 8 [34, 36, 47-51, 56]. This bidirectional converter employs two sets of full bridges and provides the following advantages: soft switching capability based on the converter operating range, incorporation of the parasitic inductance of the transformer, lower component number and device voltage stress [47, 48, 51]. The converter can operate with a triangular modulation, one of the three available modulation techniques [50]. By using a triangular discontinuous current technique, it can provide power density and efficiency greater than the previous one, due to the full-wave synchronous rectifier operation of the secondary bridge. However, it presents high peak current values and eight active power switches.

The ZVZCS full-bridge PWM converter is shown in Fig. 9. A maximum efficiency at full load close to 95% was reported from the 2.5kW/100kHz converter [52].

The Sine Amplitude Converter (SAC) concept [54] applied to a Bidirectional DAB Series Resonant Converter (SRC) is shown in Fig. 10 [36, 39, 50, 55]. This dual active bridge attenuates switching losses by the use of a resonant capacitor in series with the leakage inductance of the transformer. By using, an appropriate modulation method, as proposed in [47], the transistor switching losses in both full- bridge sides of the converter can be eliminated providing full Zero Voltage Switching (ZVS) and approximately ZCS in all

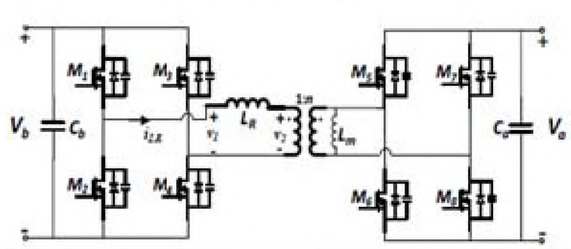

Figure 8. Triangular dual active bridge converter [47].

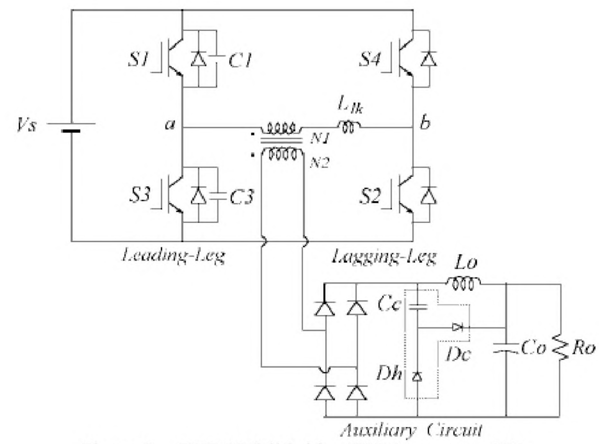

Figure 9. ZVZCS full-bridge PWM converter [52].

switches. This allows higher switching frequencies reducing the size of the magnetic components. However, the proposed technique requires frequency variation to control the delivered power. A DAB SRC converter of 1kW/500kHz, 270V-28V achieves 85.9% efficiency in 720W as reported in [47].

III. SPECIFIC ARCHITECTURE FOR HIGH PERFORMANCE TRU

Architecture to attain a High Performance TRU is obtained by applying the "Interleaving of Converters" concept, which comes from the low power applications [17, 23, 28]. It has been widely used to power microprocessors of late, and can be extended to higher power applications with interesting advantages in the specifications concerning aircraft applications.

The basic idea is to have several converters in parallel and time-shifted, processing the energy in a very smart way since the energy is spread out over space and time. This concept can offer the following advantages:

- the power is shared among several converters, obtaining a degree of freedom to improve the efficiency of the system as well as to make the thermal management easier;
- the demand of energy is spread out over time, reducing the size and weight of the required filters either the EMI filter as much as the output filter.

The interleaving concept applied to the High Performance TRU architecture is shown in Fig. 11.

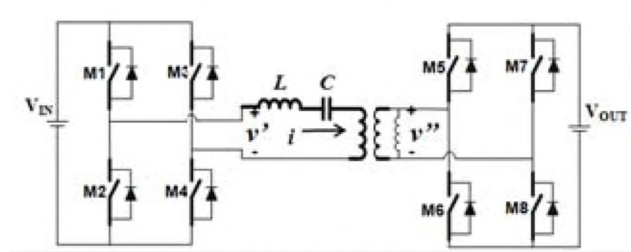

Figure 10. Resonant dual active bridge converter [47].

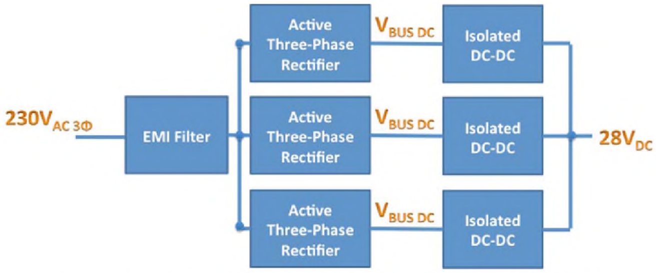

Figure 11. Interleaved of converters for High Performance TRU.

An interleaved multi-cell isolated three-phase PWM rectifier system for aircraft applications developed by CEI-UPM is shown in Fig. 12. This architecture allows high efficiency using multiple cells in parallel and high reliability with n-1 fault tolerance [28]. The ATPR based on a buck-type unidirectional topology was employed, which provides high power density and high efficiency. Also, it does not need a pre-charge circuit and it can still operate with power factor correction when one phase of the grid fails. The Full Bridge Phase Shift topology was selected for the Isolated DC-DC converter. This topology provides galvanic isolation, high efficiency, high power density, ZVS and high reliability [17, 28]. A 10kW TRU developed with battery charge capability, shown in Fig. 13, presented the following data and parameters:

- mains phase-to-neutral voltage: 115 V_{RMS}
- grid frequency: 400 Hz
- output voltage: 250 - 280V
- AC-DC switching frequency: 60 kHz
- DC-DC switching frequency: 180 kHz
- efficiency: 91%
- THD: 2.5% at full power
- power density: 1kW/kg

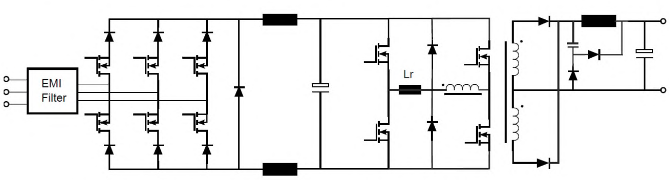

Figure 12. Buck type rectifier and DC-DC full bridge topology corresponding a one cell of the architecture presented in Fig. 11 [28].

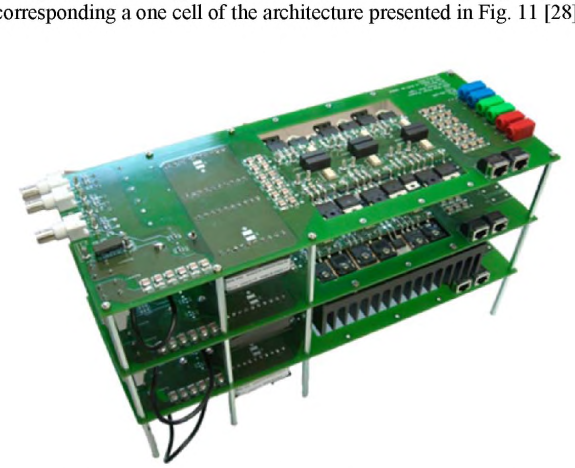

Figure 13. One cell of 10kW TRU three interleaved rectifiers [28].

IV. ADVANCED ARCHITECTURE TO HIGH PERFORMANCE TRU

Advanced architecture to High Performance TRU is based on the Isolated Three-Phase Rectifier as shown in Fig. 14. There exist some topologies that have been proposed where both functionalities, rectification and isolation, are integrated into the same converter [29, 32, 58-62]. By employing this configuration, which neglects the filter elements in the DC link of the conventional two-stage solutions, the number of required semiconductors as well as the number of inductors can be reduced thus increasing reliability. This single-stage three-phase AC-to-DC converter with high-frequency isolation of the output voltage is an interesting alternative to be considered, since it can reduce the weight and increase the power density of the whole TRU [29, 32, 58-62].

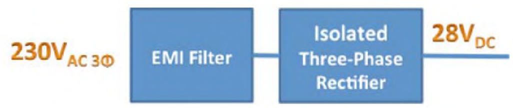

Figure 14. Isolated Three-Phase Rectifier for High Performance TRU.

In 1985, Ziogas introduced a switch-mode-rectifier (SMR) converter with sinusoidal input current and isolated output DC voltage [58]. It is a quasi-single-stage buck-derived bridge, shown in Fig. 15, as presented in [32]. Since it draws high-quality current from the AC source, requiring small input reactive components, this converter can exhibit high power density with low cost. Experimental results from a 3kVA were reported to verify the SMR converter operation [58].

In 1987, Ziogas proposed a three-phase inductor fed SMR topology. This is a quasi-single-stage boost-derived bridge, shown in Fig. 16, as presented in [32]. The advantages of this SMR converter include high input power factor, improved reliability, high power density, minimum input line current harmonic distortion, high-frequency ohmic isolation between the input and output with a suppressed DC link capacitor and the input filter AC capacitors are eliminated. Also, as the proposed SMR topology uses a front end reactor, it also has an improved reliability against short circuits [59].

In 1995, Vlatkovic introduced a three-phase, single-stage, isolated PWM rectifier [60]. The converter, shown in Fig. 17 as presented in [61], is capable of achieving unity power factor, low harmonic distortion of input currents, and at the same time performs zero-voltage switching for all power semiconductor devices. A 2 kW/100 kHz converter attained 93% of the conversion efficiency [60].

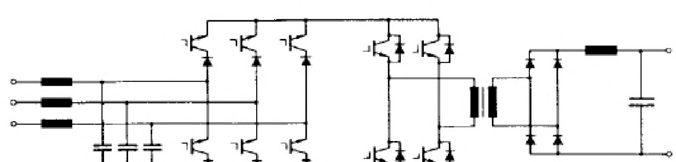

Figure 15. Quasi-single-stage buck-derived bridge [58].

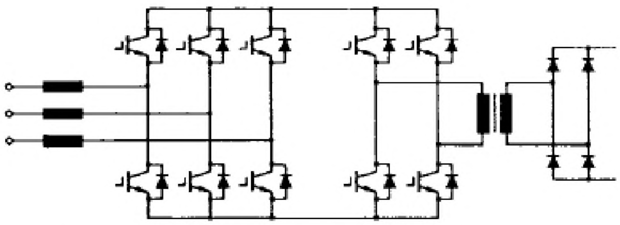

Figure 16. Quasi-single-stage boost-derived bridge [59].

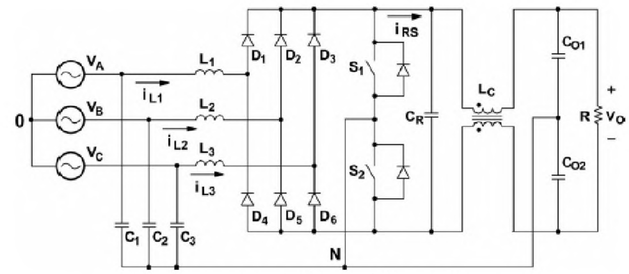

Figure 18. TAIPEI rectifier [62].

A three-phase two-switch ZVS PFC discontinuous-current-mode (DCM) boost rectifier, called the TAIPEI rectifier, shown in Fig. 18, was introduced in 2013 by the authors of [62, 63]. The rectifier achieves less than 5% input-current THD over the entire input range and over 25% load and its features perform ZVS on the switches. In addition, it offers automatic voltage balancing across the two output capacitors connected in series, and exhibits low common-mode EMI noise. A three-phase 2.8kW with 780V of the output voltage, operating in the line voltage range of 340–520$V_{L\text{-}L,RMS}$ presented the input-current THD at 380 and 480$V_{L\text{-}L,RMS}$ of 1.4% and 2.8%, and the switching at full load of 50 and 98 kHz, respectively. The full-load efficiency was in the 97.6–98.2% range [62].

A High Performance TRU based on the Swiss rectifier [19, 20, 57] developed by CEI-UPM is shown in Fig. 19 [29]. This quasi-single-stage isolated three-phase rectifier is formed by a diode-bridge, three bidirectional switches along with two DC-DC buck converters and an active third harmonic current injection.

The Swiss-Forward Converter is an interesting alternative to the six-switch buck type rectifier due to the lower transistor losses. In addition, it is easier to control since it has just two high frequency transistors and can reduce the weight and increase the power density of the whole TRU [29]. However, the Swiss and Swiss-Forward Rectifiers, present problems when two lines have the same voltage creating low frequency distortions in the line current generating high THD. This can be attenuated by increasing the input capacitance, but this negatively affects the power factor of the rectifier. A 3.3kW TRU has been developed, as shown in Fig. 20, and presented the following data and parameters:

- mains phase-to-neutral voltage: 115V_{RMS}
- grid frequency: 400Hz
- output voltage: 250 - 280V
- AC-DC switching frequency: 100kHz
- efficiency: 91%; THD: 4.5% and power factor: 0.95

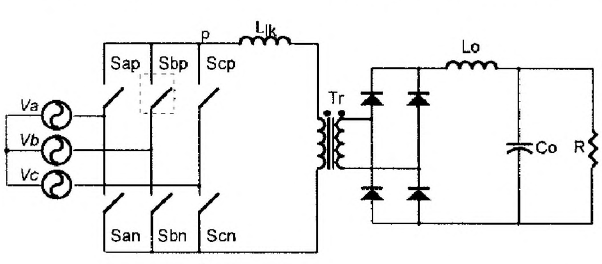

Figure 17. Three-phase single-stage isolated PWM rectifier [60, 61].

Additionally, some other selected topologies can be considered as possible candidates for Advanced Architecture to High Performance TRU as those presented in [64, 65].

V. Conclusions

This paper presented some architecture proposals, which can be employed to obtain High Performance TRU. The conventional structure is based on the EMI Filter, the Active Three-Phase Rectifier and the Isolated DC-DC converter. Four promising topologies for the Active Three-Phase Rectifier were presented, which can be employed to perform a High Performance TRU with high efficiency and power density. In addition, four options to accomplish a high performance isolated DC-DC converter were presented. The interleaving concept applied to a 10kW High Performance TRU, developed by CEI - UPM, with isolation and battery

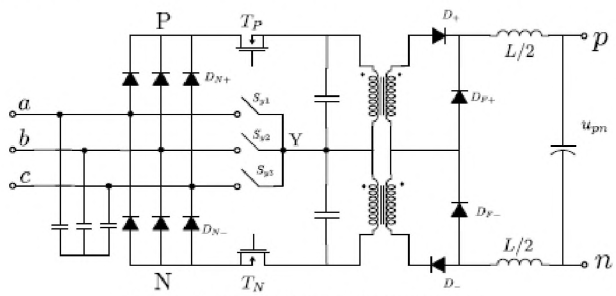

Figure 19. Swiss-Forward Converter [29].

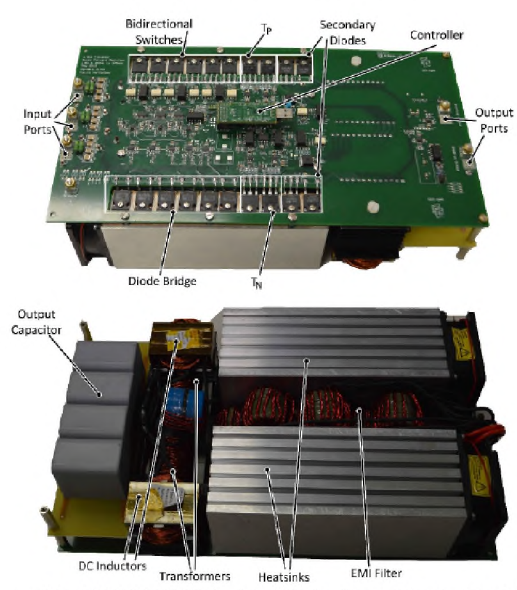

Figure 20. 3.3kW-100kHz isolated Swiss-Forward converter [29].

charge capability, obtained by using three Active Three-Phase Rectifier and three Isolated DC-DC converters, was also presented in the paper. Finally, five quasi-single-stage isolated three-phase rectifiers were presented, which are examples of the advanced architectures to High Performance TRU. One of these, the Swiss-Forward Converter, developed by CEI-UPM was described. It is a quasi-single-stage isolated three-phase rectifier formed by a diode-bridge, three bidirectional switches and of two DC-DC buck converters and an active third harmonic current injection.